Facilitating Coastal Stormwater Management in North Carolina: Runoff Estimation and Institutional Education

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Abstract
In coastal North Carolina, increased surface runoff from urban, agricultural, and forestry development contaminates coastal waters and has led to extensive shellfishing area closures. Coastal communities looking to restore their waters become eligible for restoration funding when they complete watershed restoration plans with numeric pollutant reduction goals. In this work, I present a new geospatial analysis tool for calculating modern and historic stormwater runoff estimates, which can be used as proxies for restoration goals. This tool uses satellite-derived land cover, soils, and precipitation data to provide stormwater estimates using a watershed boundary as the minimum required input. Additionally, to improve the accuracy of estimates, the tool has optional inputs for the proportion of impervious surface that is disconnected in the watershed and for areas drained for forestry operations. I compare the results from this estimator with the more labor intensive methods used in previous stormwater management plans and with estimates from SWARM (Stormwater Runoff Modelling System), recently developed by NOAA. Finally, I provide recommendations for how to best integrate these tools into the current management framework.

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I. Introduction

In coastal North Carolina, urban, agricultural, and forestry development has led to increased surface runoff and degraded water quality (Mallin et al. 2001, Richardson & McCarthy 1994, Lebo & Herrmann 1996). As stormwater washes over the landscape, it picks up contaminants and transports them into the estuarine system (Mallin et al. 2000). Oysters and other shellfish concentrate bacteria and pathogens, rendering them unsafe for human consumption (Tibbetts 2004). The Shellfish Sanitation and Recreational Water Quality office (Shellfish Sanitation) has declared large areas of North Carolina's coastal waters to be permanently closed to shellfish harvesting due to the frequency and magnitude of bacterial pollution in those areas (closed areas can be found here: http://portal.ncdenr.org/web/mf/shellfish-closure-maps).

To reopen shellfishing grounds, coastal communities can work to reduce the volume of stormwater that makes it to the estuary, thus reducing the bacterial load that enters the water. Coastal communities can qualify for restoration funding from the state and from the U.S. Environmental Protection Agency (EPA) by crafting watershed management plans. These plans are required to have quantitative goals for restoration (EPA 2008). Plans can use historic stormwater volumes as proxies for goals as they represent conditions when there was less runoff and fewer, less severe shellfishing closures (City of Wilmington 2012).

Stormwater volume estimates were included in the Bradley and Hewletts Creeks Watershed Restoration Plan to satisfy the need for quantitative restoration goals (City of Wilmington 2012). The methods used for these estimates were developed by engineers at the firm Withers & Ravenel while under contract to the North Carolina Coastal Federation. These methods rely heavily on laborious manual land cover analysis and require both time and knowledge in order to complete. Additionally, although the methods require a great deal of high resolution classification, the analysis relies on simplified data products and has not been validated against observed storm events (personal communication, H. Freeman & D. Wiebke of Withers & Ravenel). More recently, Blair et al. (2014) have created a simplified set of methods that relies on more easily obtainable data and has been validated with comparisons to observed events (Stormwater Runoff Modeling System or SWARM). However, this tool still has limitations to its ease of use and requires the extraction of data through a GIS.

II. GIS Stormwater Calculator (see Appendix A for detailed use instructions)

To address the need for a user-friendly automated tool to calculate stormwater runoff volumes, I have developed the automated GIS Stormwater Calculator. The tool was developed to run with ArcGIS version 10.2, produced by ESRI. This is a useful tool for environmental managers, municipal planners, and others interested in the quality of their coastal waters. The tool package is suitable for calculating stormwater runoff estimates for coastal North Carolina for 1992, 2001, and 2006. These years correspond to the available land cover datasets.

The GIS Stormwater Calculator addresses the shortcomings of the previous methods and integrates the data acquisition directly into the runoff tabulation. The tool requires only a watershed boundary file to perform the calculation and returns a table with runoff estimates for the one-year, 24-hour storm event for 1992, 2001, and 2006. Additionally, the tool provides the user with options in order to dial in estimates based on additional knowledge of the watershed. With integration into the management framework, this tool will facilitate coastal communities in their pursuit to improve their local water quality.

Summary of the Process

The basic function of the stormwater calculator is to tabulate a composite runoff curve number (CN) for an input watershed, which is then used to calculate runoff volume (as detailed below). The CN is a parameter that describes how well the landscape is able to retain and infiltrate precipitation. This depends on the characteristics of the underlying soil as well as the land use conditions on the surface. Each combination of these factors defines a soil-cover complex. Curve numbers have been developed empirically for each of these combinations and are published in the United States Department of Agriculture Technical Report 55. The tool tabulates the proportions of each soil-cover complex in the watershed and uses established curve numbers to generate a composite curve number for each year of data. Using the input precipitation depth, the tool uses these composite CNs to calculate runoff estimates.

Data Requirements

The GIS Stormwater Calculator requires, at minimum, land cover, soils, and precipitation data in addition to a watershed boundary. The calculator package that I developed includes land cover, soils, and precipitation data for eastern North Carolina, pre-formatted and hard-wired into the tool. Thus, all the user has to provide is the watershed boundary file.

Watershed Boundary File

A watershed is defined by all of the upstream area that drains to a given point. Input watershed files for the GIS Stormwater Calculator can be either shapefiles or feature classes in a geodatabase. There are a number of tools and methods available for delineating watersheds, but one that is easy to use and readily available is based in an application called StreamStats. This is an interactive mapping program developed by the United States Geological Survey (USGS) and state partners (the application for North Carolina is available at http://water.usgs.gov/osw/streamstats/north_carolina.html). In this interactive mapping environment, a user can zoom into the area that they are interested in and then define their watershed using the 'Watershed Delineation from a Point' tool (the icon is a black dot with a small black cross below and to the right of it).

I used ten watersheds to test the GIS Stormwater Calculator and compare results (Maps 1 & 2). These watersheds represent a range of development conditions with some highly urbanized and some primarily in agriculture. Five of these watersheds have stormwater based management plans in place (Bradley Creek and Hewletts Creek (City of Wilmington 2012)) or in development (Howe Creek, Mattamuskeet Drainage Association, and Williston Creek). The runoff volume calculations used for these management plans were calculated by Withers & Ravenel. I obtained the watershed boundary files from the engineers in order to make comparisons. Four of the watersheds have management plans but do not have specific runoff reduction goals (Dubling Creek, Boathouse Creek, Hills Bay, and the Highway 24 Area (North Carolina Coastal Federation 2009)). These watersheds, in addition, to the Deer Creek watershed, were delineated using the North Carolina StreamStats application mentioned above.

Land Use Data

The land use data is from the Multi-Resolution Land Characteristics Consortium's National Land Cover Database (http://www.mrlc.gov/) (Map 3). There are currently three land cover datasets available, from years 1992, 2001, and 2006. These data were developed through the classification of satellite imagery (Homer et al. 2007).

Soils

The soils data are from the National Resources Conservation Service's Soil Survey Geographic Database (SSURGO), downloaded through an interactive mapping service provided by Esri (web application available here: http://www.arcgis.com/home/item.html?id=a23eb436f6ec4ad6982000dbaddea5ea) (Map 4). These data are packaged at the river basin level. Although these data include many attributes, the pertinent parameter for volume calculation is the Hydrologic Soil Group (HSG). Soils can fall into four simple HSG categories (A, B, C, & D) and three dual categories (A/D, B/D, C/D), where 'A' soils are soils that have the highest runoff infiltration capacity. Dual classifications define the infiltration characteristics of soils that have very high water tables. The 'D' characterization describes the soil when it is undrained, while the 'A', 'B', or 'C' characterization describes the soil if it is drained (USDA, NRCS 1986). For this project, all soils with dual classifications were assigned soil types of 'D' as is consistent with earlier runoff models (Blair et al. 2014).

Precipitation

The precipitation data are available through the National Oceanic and Atmospheric Association (NOAA) (available here: http://dipper.nws.noaa.gov/hdsc/pfds/). The tool uses an interpolated raster layer for the storm with an average 1-year return time over a duration of 24 hours (Map 5). This is the standard model storm used in North Carolina stormwater management planning (NCDWQ 2007).

Data Preparation & Processing

In order to maximize the ease of use of the GIS Stormwater Calculator in eastern North Carolina, I packaged the necessary data with the tool. Prior to using these datasets in the tool, I projected them to the North Carolina State Plane projection. I also reduced their extent to the coastal region to minimize the size of the package. Additionally, I created a mask dataset of the coastal area from one of the land cover datasets. This is used in the model to define the projection and cell size of output data and to provide a template for raster datasets to snap to.

During the geographic analysis, first, the tool takes the watershed layer and uses it to clip the incoming polygon soils data. Then the watershed boundary is converted to a raster and used to clip incoming raster data to the size of the watershed (i.e. precipitation and land cover data) and as a mask for converting the soils data to a raster. Precipitation is calculated from the mean value of the clipped precipitation raster. Once all incoming data have been properly sized and converted to raster format, the tool moves to defining the proportion of area in each soil-cover complex.

Soil-Cover Complexes & Composite Curve Number Tabulation

In order to create a dataset that encodes all the necessary information for soil-cover complexes, I first multiplied the soils raster by 1000. This gives a raster with values of 1000, 2000, 3000, and 4000 corresponding to soils of HSG A, B, C, and D, respectively. Then I multiplied each of the land cover rasters by 10 giving raster datasets with values in the hundreds. If impervious surface rasters are used in the calculation (see the 'Options' section below for more information), they are left as is, taking values of 0-100. Finally, these rasters are added together, giving a four digit code that identifies the soil type (first digit), land cover type (second and third digits if the second digit is non-zero), and the percent impervious cover if applicable (last two digits).

The program then builds a dictionary of curve numbers by both referencing a table of numbers for each land cover class (see Appendix B) and calculating curve numbers for all impervious surface proportion possibilities. The tool then runs through each line of the attribute table of the hybrid soils-land cover raster and the code is broken apart and used to lookup the appropriate curve number in the dictionary. This CN is multiplied by the area of the cells with that soil-cover complex. These weighted curve numbers are summed and after going through each line in the table, the program computes the weighted average of all the curve numbers by dividing by the total watershed area. This returns the composite curve number.

Runoff Calculation

Once the program has computed a composite curve number for a given dataset, it uses the following calculations to find the total runoff. The basic runoff calculation is shown in Equation 1 (USDA, NRCS 1986).

Eq. 1: $Q = (P - I_a)^2 / ((P - I_a) + S)$

Where:
Q is the depth of runoff (inches)
P is the depth of rainfall (inches)
I_a is the initial abstraction (inches)
S is the maximum potential retention (inches)

The curve number is integrated in this equation through its relationship with S (Equation 2) (USDA, NRCS 1986).

Eq. 2: $CN = 1000 / (10 + S)$

The initial abstraction value (I_a) is not calculated from the data, but rather is dependent on an empirically derived relationship with the maximum potential retention (S). Originally, this relationship was described with $I_a = 0.2S$. However, more recent analysis suggests that an estimation of $I_a = 0.05S$ is more appropriate (Blair, et al. 2014 & Woodward, et al. 2003). S values derived from CNs from the NRCS TR-55 can be transformed to fit this relationship as shown in Equation 3 (Woodward et al. 2003).

Eq. 3: $S_{0.05} = (1.33S_{0.20})^{1.15}$

Where:
$S_{0.05}$ is the transformed maximum potential retention value when $I_a = 0.05S$
$S_{0.20}$ is the initial maximum potential retention value when $I_a = 0.2S$

Corresponding curve numbers can be transformed through equation 4 (Blair et al. 2014).

Eq. 4: $CN_{0.05} = 100 / (1.879(100 / CN_{0.20} - 1)^{1.15} + 1)$

Where:
$CN_{0.05}$ is the transformed composite curve number when $I_a = 0.05S$

$CN_{0.20}$ is the composite curve number calculated from the relative proportion of soil-cover complexes and their curve numbers in TR-55 where $I_a = 0.2S$

Using these equations, first the S value is transformed and then used in the runoff equation (Equation 1) to calculate runoff in inches. This value is multiplied by the area of the watershed (in square feet) and divided by twelve to give the runoff volume in cubic feet. The program also converts this value to acre-feet and computes the transformed curve number for output.

Usage and Output

The GIS Stormwater Calculator package is an independent workspace that is distributable by a single compressed .zip file. The tool package was developed to function in ArcGIS 10.2, by ESRI. Once decompressed, the workspace holds five folders: Data, which holds the necessary data for the tool to run; Documents, which holds documentation information; Results, which is an empty folder but can be used for output tables; Scratch, which is where all intermediate products of the tool are held; and Scripts, which holds the script that defines the operation of the calculator. Additionally, in the workspace there is: an ArcMap document to perform the calculations in and to visualize the data; a toolbox, which holds the stormwater calculator script tool; a copy of the Custom SWARM Excel tool; and a readme document that provides some simple information about when the tool was produced and author attribution.

The tool can be accessed through the accompanying map document. In the ArcToolbox window, the only toolbox available will be the Stormwater Calculator where the script tool resides. Any watershed boundary data should be placed in the Data folder of the workspace before proceeding with calculations. Some example data is provided within the Data folder in a folder called 'ExampleData'. This has a watershed boundary file as well as shapefiles for hypothetical drained forest areas for reference on how that option works and what affect it has. Finally, the user must be sure that the workspace resides on a local drive – running the calculator remotely greatly increases the chances that it will fail.

The GIS Stormwater Calculator has one main output – a tab delimited text document containing the stormwater runoff estimates for the input watershed. This document can be opened easily in Excel to show the table of runoff estimates (see Table 1 for an example output). The tool also writes an .xml file to the same location as the output table. This contains a summary of the input parameters used in the tool. If the user is interested in comparing the results of the 2001 and 2006 calculation, would like a land use or soils summary of the watershed, or would like the precipitation value used, checking the SWARM table output box and providing a path will write this information into a text file (see 'Options' section for more details).

III. Validation of GIS Stormwater Calculator using SWARM Methods

The Stormwater Runoff Modeling System (SWARM) was developed recently to address the need for a simple model for watershed runoff dynamics. This modeling system allows users to estimate storm runoff as well as produce hydrographs (representations of runoff over time for a storm event). Through validation testing against recorded storm events, Blair et al. (2014) demonstrated that the model is accurate and robust. Runoff estimations had relatively high accuracy, deviating 3-11% from recorded storm events. In order to capture the accuracy of this model, I used the base calculations and relevant calibration methods from SWARM. These include the transformation of S values to reflect the updated estimates of I_a (Equation 3) as well as the assumption that all developed areas take on the most impervious hydrologic soil group of D (Blair et al. 2014 & Woltemade et al. 2010). Additionally, I used the same curve numbers found in the SWARM model, save the CN for wetlands. For this land cover class, I used a CN of 98 for all soil groups as is suggested in NRCS TR-55 rather than the CN of 78 in the original SWARM tool (A. Blair, personal communication).

There are two primary limitations to the SWARM tool that the GIS-based stormwater calculator addresses. The first is the necessity of gathering and processing the input data for the calculation. Although the SWARM Excel tool is quite user-friendly, it still suffers from the need to familiarize oneself with the types of input data and runoff calculation and the need to summarize the data for input. The GIS-based automated calculator addresses this shortcoming by automatically sampling the necessary data and performing the calculation all in one step. Although GIS knowledge is still necessary, as it is inherently necessary in the process, the GIS-based tool further improves the user-friendliness of the toolset.

The second limitation of SWARM is in one assumption used in the calculation, the homogenous soils assumption. Apart from developed soils being modeled as HSG D, all other land cover classes are assumed to sit over the same proportion of soil groups as is contained in the entire watershed. This assumption eases the process of data collection for the tool and still produces relatively accurate results. However, it simplifies the complexity of the modeled watershed and can, in some cases, lead to significant differences in the results of the model (see Dubling Creek example below). The GIS-based tool I developed, is not limited by this assumption as soil-cover complexes are calculated for each cell in the data and then used to tabulate the composite curve number (see 'Data Processing' section above).

In order to test the effect of the homogenous soils assumption, I ran the GIS-based calculator using the default settings. These settings take on the same calculations and calibrations as in the SWARM tool, except that the GIS Stormwater Calculator does not make the homogenous soils assumption. For the most part, the homogenous soils assumption has little effect on the outcome of the calculation (Figures 1 & 2). All results except those from the Dubling Creek watershed were within 1.5 CN units and 2.5% of each other. The Dubling Creek watershed, on the other hand was strongly affected by this assumption, varying by nearly 15% or 8.4 CN units (Figure 1, Map 3).

__Dubling Creek Example__

The Dubling Creek watershed is dominated by forest, shrubs, and wetland land covers (Map 3). Both forested and shrub land covers have high infiltration rates (curve numbers equal to 30 and 30 for A soils, 48 and 55 for B soils, 65 and 70 for C soils, and 73 and 77 for D soils, for shrub and forest, respectively). Whereas wetlands have very low infiltration rates (CN equal to 98 for all soil types) (USDA, NRCS 1986). The model of this watershed is highly affected by the homogenous soils assumption because most of the wetlands fall on HSG D soils, while a large proportion of the forested and shrub lands overlie HSG A soils (Map 3). The consequence is that if the ratio of soil types of the whole watershed is applied to each of the land cover types, the model overestimates how much runoff occurs from the forested and shrub areas. The result is a curve number that is 15% (8.4 units) higher than if it were calculated without the homogenous soils assumption (see negative outlier in Figure 1). This example shows that although the effect of this assumption is generally limited to a few percent, in some cases, it can drastically change the resulting model.

IV. Calculation Options

In addition to the default calculation that follows the SWARM model, the GIS-tool has six options that may help dial in runoff estimates. Although I have not validated that these options improve the outcome of the model, I have built them into the architecture of the tool and I provide the rational for each below. Being contained in the tool already, they provide the opportunity for validation without further development and flexibility for manipulating the model. The tool is built with the options to: enter a custom precipitation value; use impervious surface raster layers to aid in the calculation of developed area curve numbers; consider the percent of impervious surface that is disconnected for each of the calculated years and which value to use as a cutoff in this calculation; remove the assumption that all developed soils are of the HSG D; include forested areas drained for silviculture operations; and produce a table that is readily entered into the SWARM Excel tool.

Precipitation Control

The default precipitation value used in the GIS Stormwater calculator is sampled from a NOAA precipitation raster for the storm with a predicted return time of one year and a duration of 24 hours (1-yr, 24-hr storm). However, if a user wishes to use another precipitation value that may correspond to a different model storm or to a recorded storm, he or she simply can uncheck the default setting and enter their own value.

Impervious Surface Layer Integration

The second option in the GIS-tool is to use impervious surface layers in the calculation of curve numbers for developed areas. When this option is checked, the tool samples rasters with the percent impervious surface in place of any cells that are classified as developed. Using Equation 5 (USDA, NRCS 1986), the tool creates a dictionary of curve numbers for each possible percentage of impervious surface.

Eq. 5 $CN_c = CN_p + (P_{imp} / 100)(98 – CN_p)$

Where:
CN_c is the composite curve number
CN_p is the pervious curve number
P_{imp} is the percent imperviousness

The pervious curve number used in the calculation is that of developed 'Open Space' in good hydrologic condition (USDA, NRCS 1986).

The tool uses impervious surface layers from the MRLC (http://www.mrlc.gov/) that accompany the 2001 and 2006 land cover datasets. The 1992 land cover data do not have an accompanying impervious surface raster and as such, the effect of this option does not extend to the 1992 calculation. However, I have calculated an impervious surface layer for the 1992 land cover data that is only composed of impervious surface values with nearly the same curve number as the accompanying classified developed area types (Table 2). With this option checked, the 1992 impervious layer simply acts as a stand in for the classified image. This extra layer is important to provide consistency for the disconnected impervious options discussed below.

In making this substitution, the tool uses data with a higher resolution of land use and as such should improve how developed areas are modeled. Realistically, the effect of this option is fairly small (Figure 3), resulting in differences in curve numbers by less than 0.6 CN units, representing less than a one percent change. Inclusion of this option facilitates the consideration of disconnected impervious surfaces.

Disconnected Impervious Surface Considerations

By default all impervious surfaces are assumed to be connected. Traditional development practices treat stormwater as a drainage problem and use designs to remove runoff as quickly as possible from the landscape in order to avoid flooding. For example, gutters on homes drain onto the concrete, which drains to storm sewers, shuttling rainfall quickly off the landscape. These connections can be broken if runoff is directed over pervious areas to encourage infiltration. One example of this that is frequently used in residential areas is disconnecting gutter downspouts by using a flexible piece of tubing on the end of the downspout and redirecting the runoff over a lawn or garden area (North Carolina Coastal

Federation 2013). Disconnecting impervious surfaces is a common retrofit management strategy as it is generally low cost and easy to implement. Large scale efforts at disconnection can have significant effects on runoff (EPA 2007). However, it is important to note that at some level of development (i.e. level of impervious surface coverage), the benefits of disconnection are lost. At intense development levels pervious areas can be overwhelmed by runoff and their capacity to infiltrate is exceeded. The NRCS suggests that this occurs when an area exceeds 30% impervious surface coverage (USDA, NRCS 1986).

The GIS Stormwater calculator provides users with the opportunity to model historical disconnected impervious surfaces in their target watershed. When non-zero values are entered into the calculator tool prompt, the impervious surface layers are activated in the model and the tool prepares the data in a similar manner as is described in the 'Impervious Surface Layer Integration' section above. The only difference is that the tool uses Equation 6 (USDA, NRCS 1986) to calculate curve numbers up to the disconnected impervious cutoff specified in the tool (the default is equal to 30 as this is the suggested cutoff in TR-55) and enters them in the curve number dictionary. Curve numbers for the levels of imperviousness above the cutoff are calculated with Equation 5 and entered into the dictionary.

Eq. 6 $CN_c = CN_p + (P_{imp} / 100)(98 - CN_p)(1 - 0.05R)$

Where:
CN_c is the composite runoff curve number
CN_p is the pervious runoff curve number
P_{imp} is the percent imperviousness
R is the ratio of disconnected impervious area to the total impervious area

The impervious surface raster for 1992 is important here because it allows the tool to sample the disconnected curve numbers at the proxy impervious level if they are under the cutoff. Again, the effect is somewhat limited with this dataset because of the singular impervious surface percentages assigned to each development land use class, but this will still provide a modified curve number that may better describe the developed landscape at the time.

This option provides users with two benefits. First, it may allow them to more closely model their historical runoff volumes. Secondly, it allows users to experiment with different disconnected impervious percentages giving them an idea of how different levels of disconnection will help them achieve their management goals.

Urban Soils HSG Designation

Although the default calculation assumes that all developed soils are in the HSG D, the tool provides an option to ignore this assumption. If ignored, the tool references a different curve number reference document to form the curve number dictionaries. This option is available primarily so that users can compare the output from the tool with other estimation techniques that may not make the same assumption (see 'Comparison to Earlier Methods' section for more discussion).

Drained Forest Areas

Much of coastal North Carolina contains managed forests. Ditching and draining forests alters the hydrology of these areas and leads to higher runoff (Lebo & Herrmann 1996). The GIS Stormwater calculator gives the user the option to include ditched and drained forests in the model.

This option relies on the user to provide the necessary spatial data. The inputs for this option are polygon feature datasets of areas with drained forests for each year of the calculation. When this option is selected and the data provided, the tool reclassifies any pixels of the land cover image that both intersect the polygons and are classified as forest. The reclassified pixels draw from a different entry in the curve number dictionary, which corresponds to forested areas in poor hydrologic condition (Table 3).

This option is primarily intended to assist users who are modeling heavily forested watersheds.

Generate SWARM Input Table

The final option of the tool is to generate a simple text file with all the information necessary for the SWARM Excel tool (Table 4). This table includes the precipitation value used in the calculation, the area of each soil class in the watershed, and the area of each land cover class in the watershed. Included with the tool is a custom SWARM Excel calculation workbook based on a template created by NOAA's National Ocean Service, National Centers for Coastal Ocean Science. This contains an extra worksheet that is formatted to accept this information with minimal pre-processing. The workbook then performs the standard SWARM calculations and returns composite curve numbers and volume calculations. The primary purposes of this option are to allow the user to check the results of the GIS Stormwater Calculator and to investigate how the assumption of homogenous soils affects their results.

GIS Stormwater Calculator Limitations

The primary limitation of the GIS Stormwater Calculator is that it is currently only designed for use in coastal North Carolina. In order to develop the most user-friendly tool possible for users in the area, I included the necessary data in the package and hard-wired it into the tool. This, however is not a very difficult limitation to overcome. To increase the applicability of the tool, the script needs to be modified to redefine the input parameters to accept custom soils, land cover, and precipitation data. A few extra steps would need to be added to ensure that the data provided by the user is of the right type and will function in the tool.

Another limitation stems from the necessary input land cover data. The earliest classified land cover data available is from 1992, after development on the coast of North Carolina had been underway for decades. Therefore, the calculator is not able to produce a baseline watershed runoff estimate that represents the natural level of runoff before the effect of humans. If regional classifications are available or developed, these may be integrated into the tool with some modification.

Additionally, the land cover data presents two other limitations to the tool. The first is that the 2001 & 2006 data were processed in a slightly different way than the 1992 data and as a result have some differences in the classification classes – primarily the developed classes. I have done my best to assign the most appropriate curve numbers to the 1992 data, but the accuracy of the runoff numbers has not been validated and they likely have more error than the later estimations.

The second limitation is one of scale. The land cover data is available at a resolution of 30 meter by 30 meter cells. The resolution of the data prevents this tool from being used to model project sites or other small areas that managers may be interested in. Rather, the tool is best fit to model larger areas, such as the watersheds used in this project.

Finally, the options currently provided in the tool are unverified as to whether or not they improve the accuracy of the model. Although most of these options use accepted formulae, it is important to test whether they provide an additional calibration measure to the tool.

Future Directions

Much of the future opportunity for the GIS Stormwater Calculator is in addressing limitations of the tool. The continuing development of the tool should begin with modifications to allow users, regardless of their location of interest, to use the tool. Providing input options for location specific land cover, soils, and precipitation data would achieve this. Importantly, wider applicability and distribution of the calculator will allow more validation tests to be performed.

One important step after modifying the tool for wider applicability is to retest the validation events used in the SWARM model (Blair et al. 2014). Running the calculator on the default settings will give back volumes that were computed in the same manner as the SWARM method but without the assumption of homogenous soils. The results will show the true effect of that assumption on accuracy. Additionally, the options of the GIS Stormwater Calculator can be evaluated by validation. Their effect on the accuracy of the model can be tested and the results can inform us whether there needs to be further model calibration.

Finally, as new land cover data is developed it needs to be integrated into the tool. This will provide more modern estimates of runoff volume and better inform users about the current conditions in their watershed of interest.

V. Comparison to Earlier Methods (Withers & Ravenel)

The North Carolina Coastal Federation has been using historical stormwater estimates in watershed plans they have contributed to, with estimation methods developed to define goals for the Bradley-Hewletts Creek Watershed Restoration Plan completed in 2012 (City of Wilmington). An engineering firm, Withers & Ravenel, led the development of these estimation methods. These methods follow the same basic procedure that is embodied in the GIS Stormwater Calculator – they use NRCS methods to compute a composite curve number and then use that to calculate runoff using Equation 1 above. These methods, however, do not have any of the calibration elements contained in GIS Stormwater Calculator or SWARM. There is no transformation of S and developed soils are not assumed to take on HSG D. However, all residential impervious surfaces are assumed to be 50% disconnected, not limited by any value of the total impervious surface coverage.

One of the fundamental differences in the methods developed by Withers & Ravenel is the method for characterizing land use. Where the GIS Stormwater Calculator and SWARM use satellite based land cover data, the engineers used higher resolution aerial photographs. Using these photographs, the analyst first builds a polygon dataset, drawing individual shapes around areas with similar land use – residential neighborhoods, commercial development centers, or forested areas, for example. For each of these shapes, the analyst makes an estimation of the proportion of impervious surface and writes it into an attribute. Using this as a template the analyst compares the polygon data with each year of aerial photography, modifying the shapes and impervious surface proportions as necessary. Once all years have been characterized, the analyst can then intersect those land use data with soils data, export the resulting tables and use them in the NRCS volume calculation.

After these methods were initially applied to more rural watersheds (Mattamuskeet Drainage Association and Williston Creek), the engineers modified the land use characterization to better summarize the conditions of those areas. Rather than being able to depend on a simple comparison of impervious surface to developed 'open space,' they added a category for agriculture.

The engineers have made calculations for five of the study watersheds: Bradley Creek, Hewletts Creek, Howe Creek, Mattamuskeet Drainage Association, and Williston Creek. Unfortunately, the years of the engineer's calculations do not directly correspond to those from the GIS Stormwater Calculator. Thus, I could not make direct comparisons. However, I ran the GIS Stormwater Calculator with the same assumptions that the engineers used in addition to the default settings to make a more appropriate comparison. These include the assumption that 50% of residential impervious surfaces are disconnected and that developed soils do not automatically take on HSG D. The method I used to mimic consideration of only residential soils as disconnected was to set the threshold of the disconnected impervious surface calculation to 95%. This is because commercial areas in the engineers' methods were considered to have 95% impervious surface. Thus, applying the cutoff effectively preserved the assumption of 100% connection for commercial areas.

Exploratory plotting shows some general trends in the results (Figure 4). First, the effect of considering 50% of impervious surfaces as disconnected and the preservation of developed soil types is clear in the Bradley Creek, Hewletts Creek, and Howe Creek graphs. Volume estimates are lower because infiltration is higher under these parameters. The same trend does not appear in the Mattamuskeet Drainage Association or Williston Creek graph. This is likely because these are rural watersheds with very little developed area.

Reserving the case of Williston Creek, the engineer's stormwater estimates are lower than the estimates from the GIS Stormwater Calculator. Sometimes this disparity is substantial. For example, the GIS-based estimates for Hewletts Creek are near double the estimates of the engineers. The upward slope of the estimates for the developed watersheds (Bradley, Hewletts, and Howe Creeks) is preserved in both methods. This suggests that there may have been a consistent difference in the assignment of impervious surface proportion between the engineers' data and the satellite derived data. Again, this pattern does not hold for the undeveloped watersheds. Part of this may be due to the simplicity of the land use data generated by the engineers' method. They consider agriculture but do not have separate classes for forests, brush, wetlands, or different types of agriculture (i.e. grain compared to row crops). All space that is not covered by impervious surfaces or considered to be in agriculture is treated as developed 'open space.'

These comparisons demonstrate some of the weaknesses of manually classifying land cover. First, it is non-repeatable. Assignment of impervious surface coverage is somewhat subjective – an analyst may be able to produce repeatable estimates him or herself, but the fidelity of that analysis does not hold between users. Second, although the classification types may be appropriate for developed watersheds, the simplified classifications for undeveloped watersheds likely lead to high inaccuracy for the subsequent calculations. Third, one of the greatest limitations is the time, labor, and skills necessary to complete the analysis. Finally, using aerial photographs as a land cover data source can be both a strength and weakness – there may be photographs available from earlier years than satellite classifications are available or there may be few photographs at all.

VI. Management Integration

The purpose of this project is to help facilitate stormwater planning on the coast of North Carolina. Without a pathway for implementation, this tool will not achieve this goal. Mechanisms for implementation range from centralized to decentralized in nature. Centralized pathways are focused on integrating the tool package within the existing management framework, educating participating institutions and using existing resources for calculations. Decentralized pathways focus on distributing the package widely, allowing users to comment on strengths and weaknesses and provide feedback for improvement. Successful distribution will include both of these types of pathways.

In North Carolina, there is an opportunity to integrate the tool package within the current management framework engaging with the Shellfish Sanitation section. On the coast, management efforts begin at the municipality or watershed level. Once an area of coastal waters is identified for restoration, the interested party begins to gather data about the local water quality. This includes information about the extent and severity of shellfishing closures, provided by the Shellfish Sanitation. Once the basic information has been gathered and the scope of the problem has been identified, the management goals and the plan for restoration can be completed.

The Shellfish Sanitation office is an important resource to anyone interested in improving coastal water quality. They provide data on historic and current shellfishing area closures in addition to raw data pertaining to bacterial contamination. The staff regularly engages in GIS heavy activities and has the resources to run the GIS Stormwater Calculator. As the tool package needs only a minimal input (the watershed boundary file) and takes only a small amount of effort, it seems likely that the Shellfish Sanitation section would host the calculator as a service.

There are a number of advantages to having a centralized group that offers the services of the calculator. First, the users in the section will be able to answer the questions of their clients because they have experience in the topic and they will have the most experience with the tool. Additionally, they can be directly educated on the best ways to use the options of the tool and the most appropriate applications. Secondly, any updates to the tool package can be readily distributed, as the user is a known entity and they can be contacted directly.

Distribution to a wider audience through a decentralized means is also desirable. The tool can be provided over the internet, facilitated by the North Carolina Coastal Federation as well as other entities. This will allow users familiar with ArcGIS to download the package and apply the tool as necessary. The open access nature of the package will allow users to adapt the methods to fit their own needs and improve the performance of the tool. Additionally, with a diverse user set, any bugs in the script tool can be identified and fixed. The feedback from a larger user group will help the tool move forward and maximize the accuracy and relevance of the calculations it can perform.

One important step to maximize the scope of the distribution is to generalize the tool, removing the packaged data and giving the user the opportunity to enter their own geographic specific data.

With proper distribution and integration, the GIS Stormwater Calculator can be a useful tool for community planners to begin the process of improving their local water quality. Particularly, it can help municipalities in areas with few resources secure funding for restoration of their watersheds and improve their quality of life, bringing back historical shellfishing, important to both the culture and economy of their regions.

VII. Acknowledgements

The North Carolina Coastal Federation has been particularly important in ensuring that this project has gone forward and will be implemented into the current management scheme. Additionally, Dr. Xavier Basurto has contributed many pieces of salient advice throughout the process. Anne Blair, from NOAA, was kind enough to provide the template SWARM tool and discuss future directions and critiques of the tool. Finally, Withers and Ravenel were generous enough to grant access to watershed files and information about the early methods used in coastal stormwater management plans.

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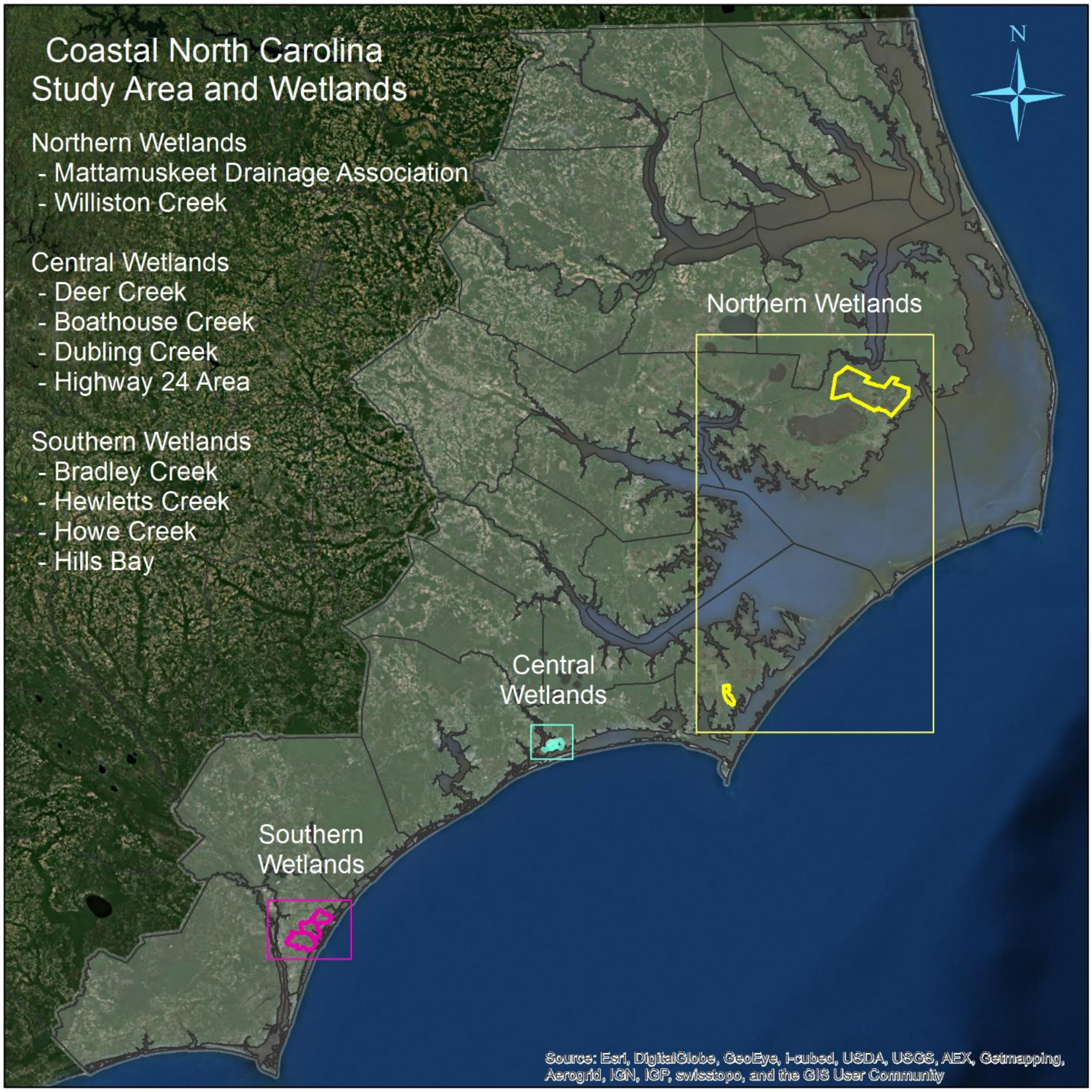
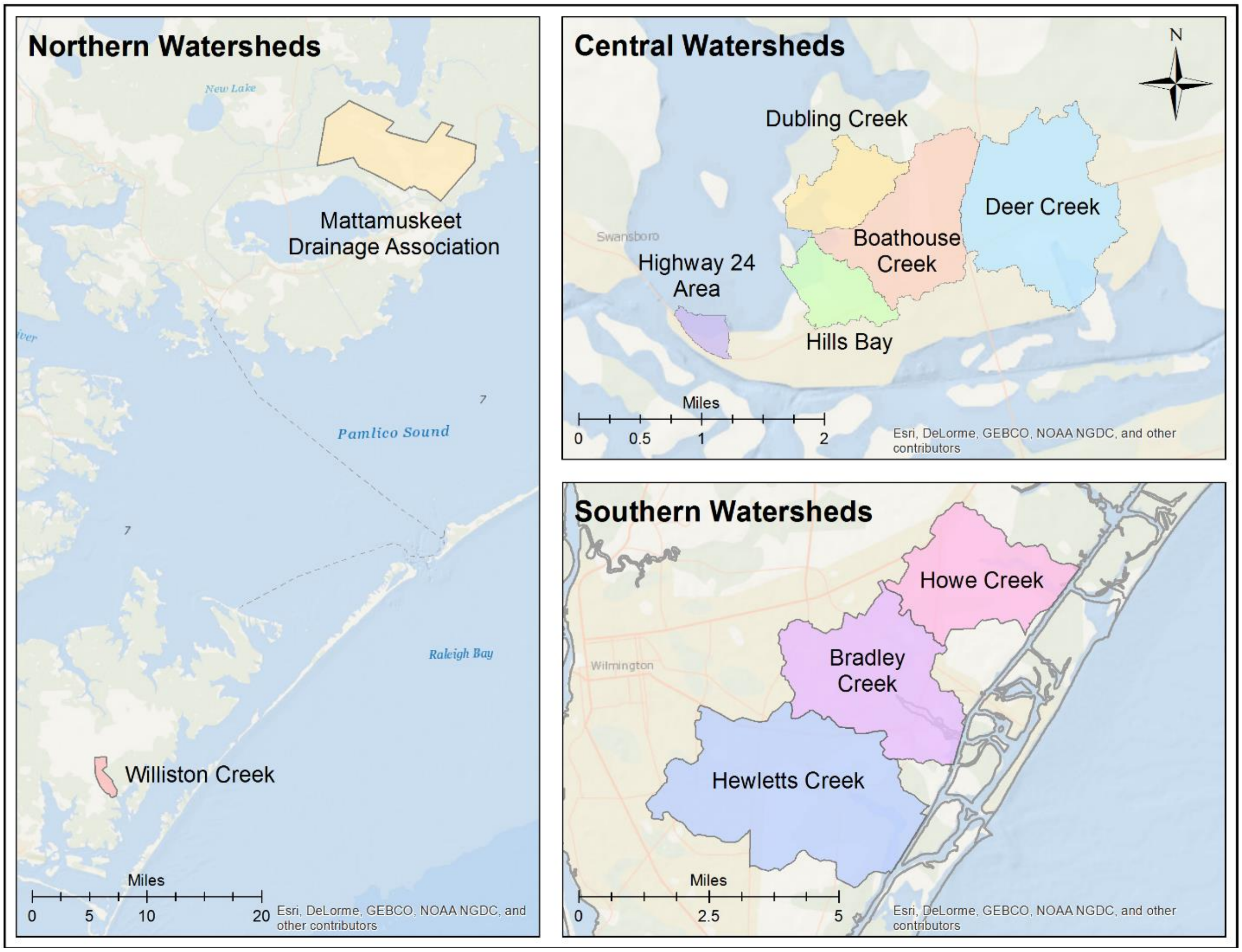
IX. Maps, Figures, and Tables

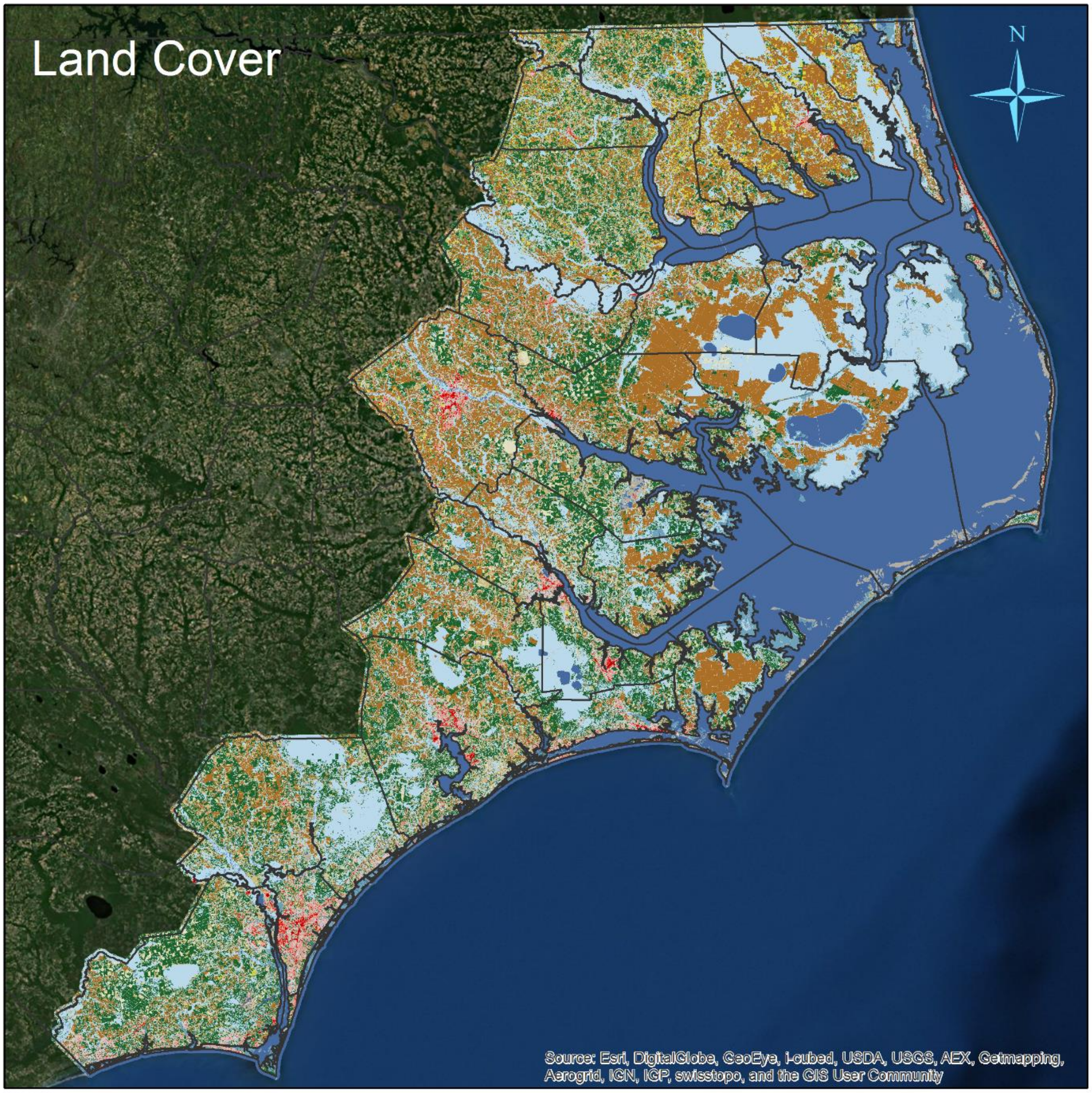
Map 1. Study Area and Watersheds. The shaded white area shows where the GIS Stormwater Tool may be applied without modification and with the prepackaged data. The three boxes on the map correspond to the extents of the frames on Map 2, which shows a more detailed view of the wetlands used in this study. There are ten wetlands that were used in this study, two in the northern area, five in the central area, and three in the southern area.



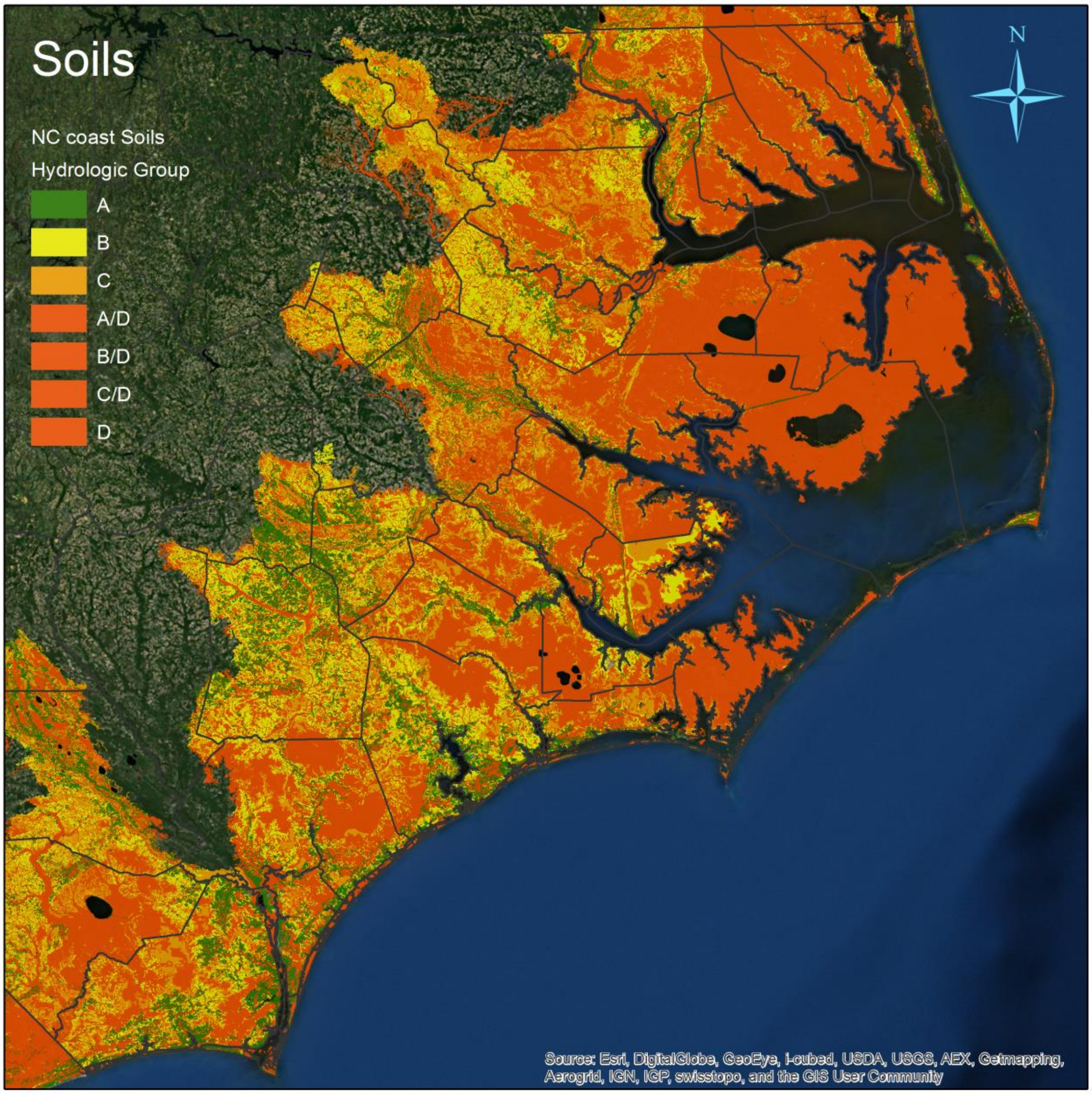
Map 2. Study Watersheds: Close-up. This map shows the relative position and size of the watersheds used in the study. The map is broken into the three regions shown in Map 1. The five watersheds in the southern and northern areas were delineated by Withers and Ravenel during their runoff estimation calculations. The five watersheds in the central area were delineated using the North Carolina StreamStats application.



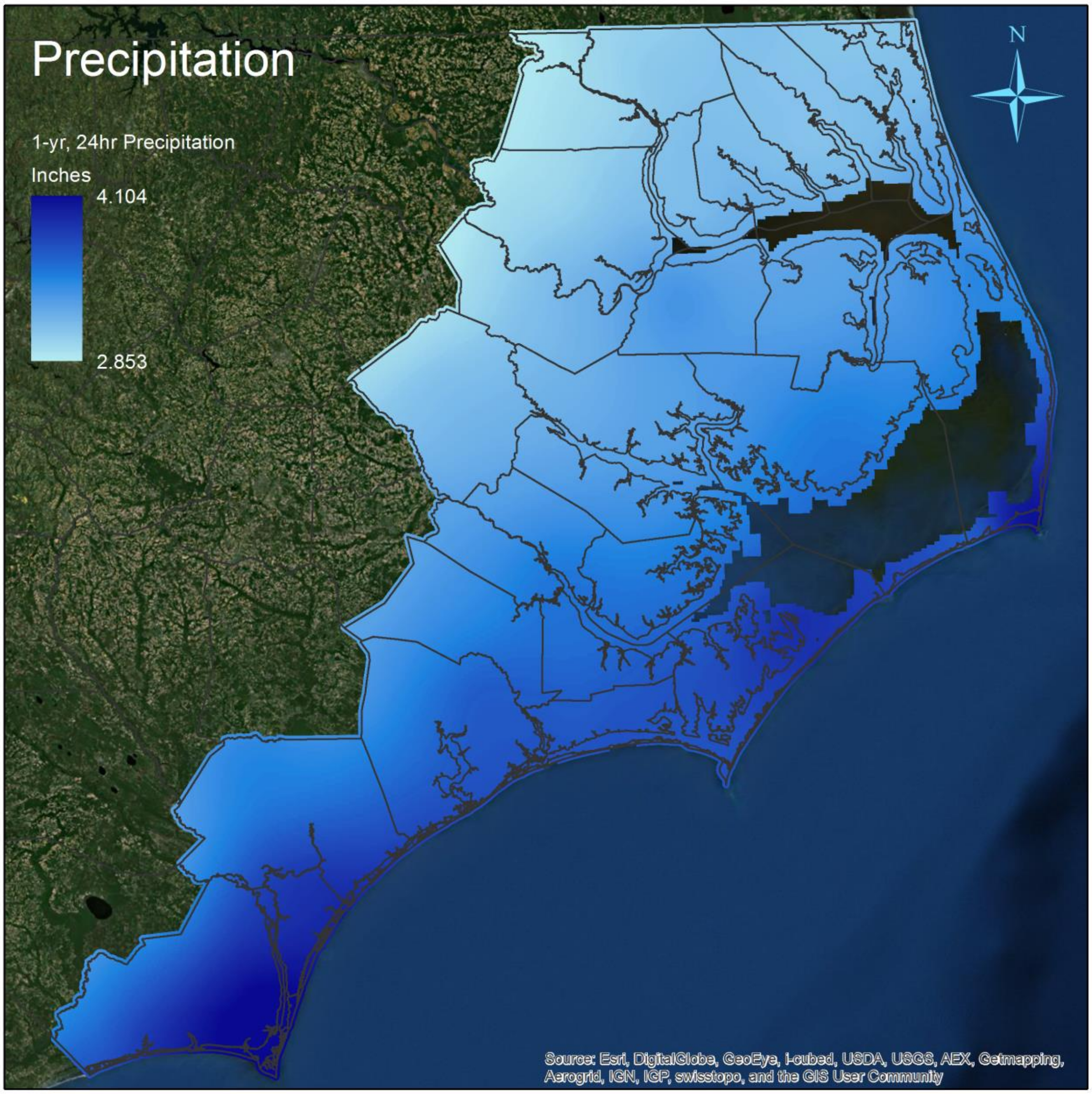
Map 3. Land Cover Data. This map shows the 2006 land cover data from the MRLC used in the Stormwater Calculator. Brown areas are agriculture, green areas are forested, pink and red areas are developed, light blue areas are wooded wetlands, and dark blue areas are open water.



Map 4. Soils Data. This map shows the hydrologic soils group data used in the Stormwater Calculator Model. This data was acquired from the NRCS SSURGO database.



Map 5. Precipitation Data. The Stormwater Calculator uses precipitation data for the one-year, 24-hour storm from NOAA.



<u>Map 6</u>. Dubling Creek Soil-Cover Complex. These four frames show how the homogenous soils assumption can affect runoff estimates. A) Orientation and location of Dubling Creek watershed. B) Soils raster of Dubling Creek watershed. C) Simplified land cover data. Forest and shrub areas were grouped together because of their similarity in runoff characteristics and all other types of land cover, save for wetlands, were grouped together as they represent a small portion of the total. D) The simplified land cover and soils were integrated to show the relative runoff from each complex. Nearly all of the wetlands overlie HSG D areas, while a large proportion of the forest and shrub areas overlie soils of HSG A and B. Assuming homogenous soil types for this watershed leads to an overestimation of the runoff curve number by nearly 15%.

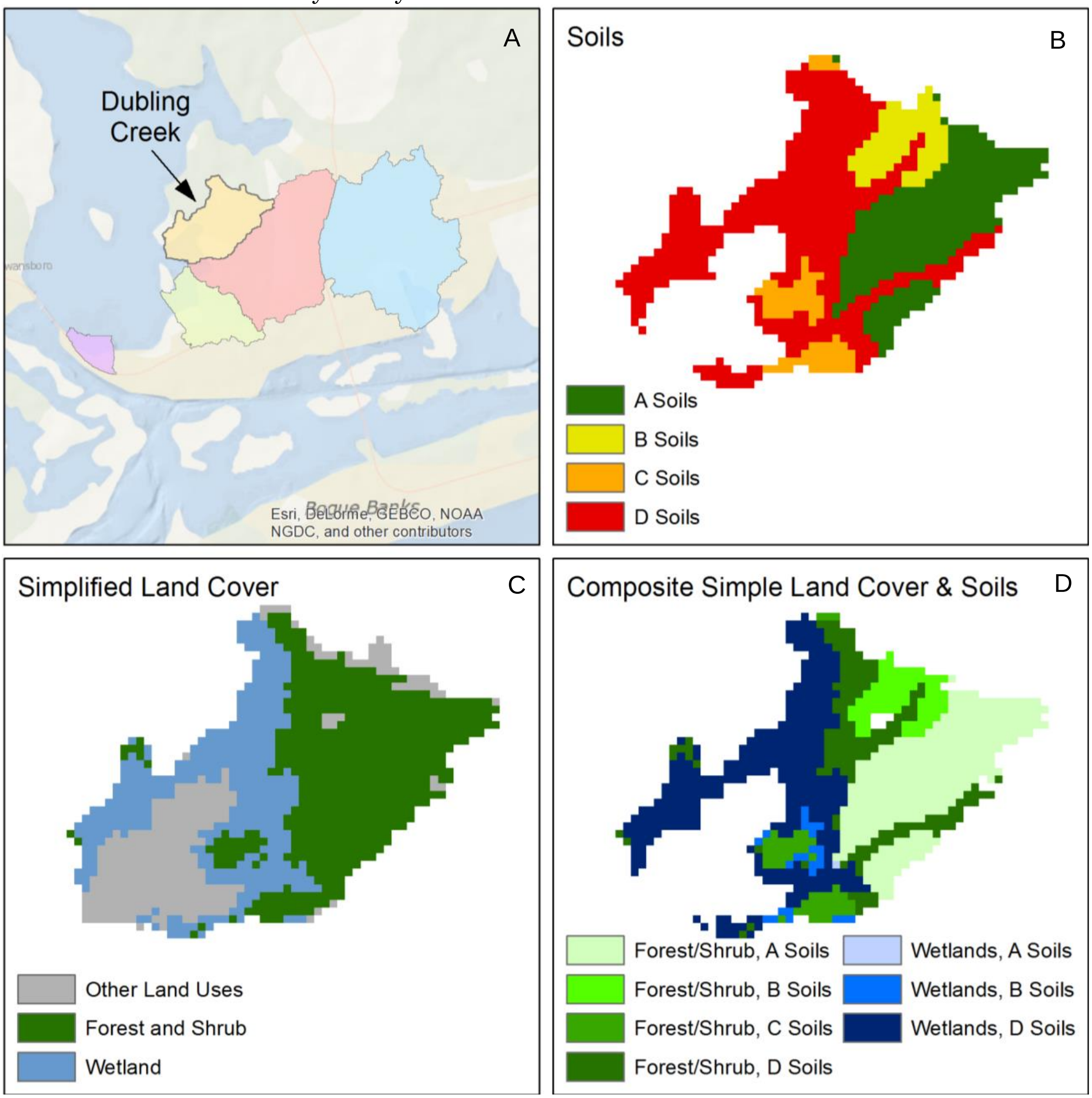


Figure1. Comparison between SWARM and GIS Stormwater Calculator results for 2001 and 2006 land cover data from all watersheds. Negative values indicate that SWARM calculations led to higher runoff values than the GIS-based calculator. The difference in results is due to an assumption in SWARM that the proportion of each soil type in the watershed is equal to the proportion of each soil type underlying each land cover type. The large outlier corresponds to the Dubling Creek watershed.

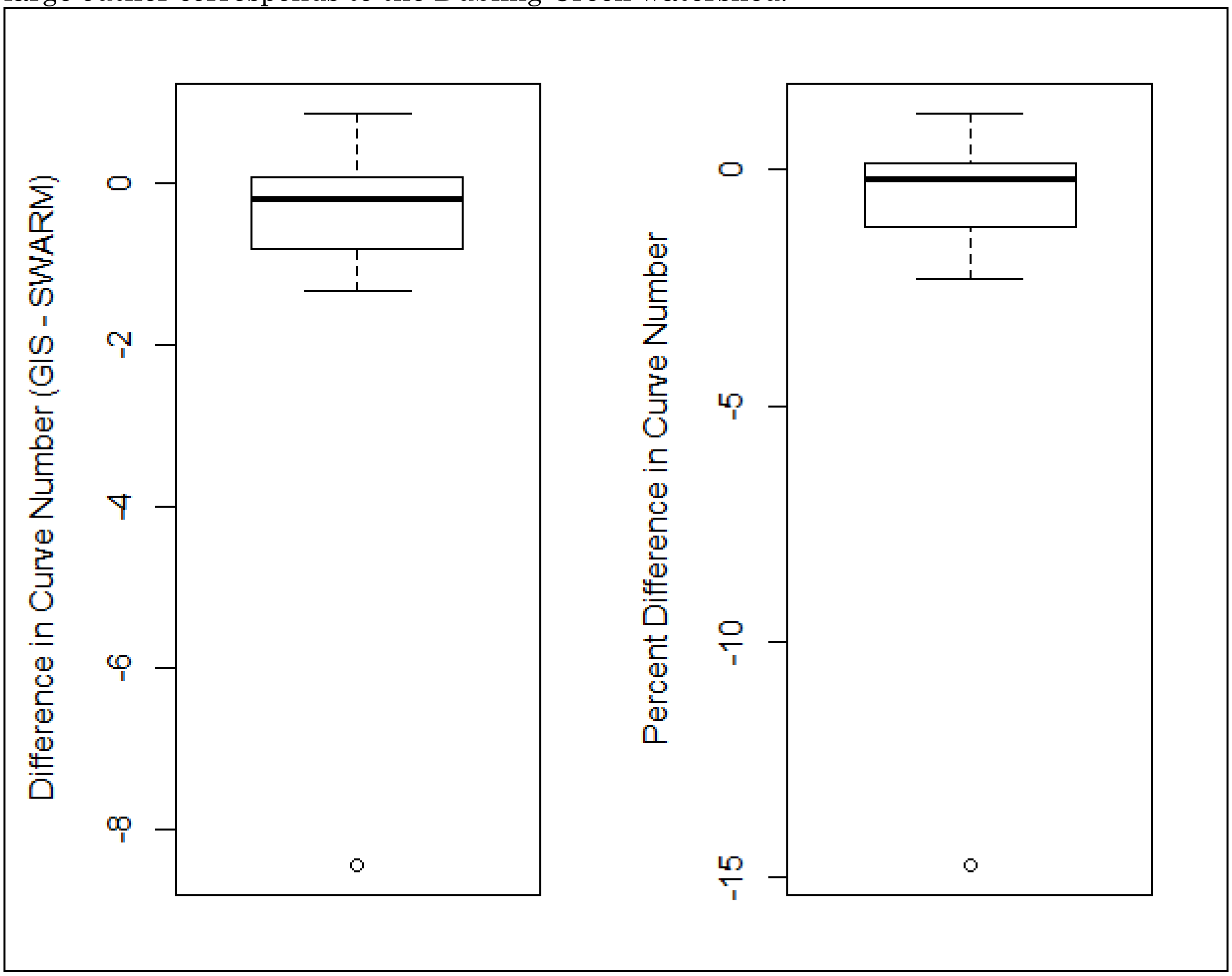


Figure 2. Pairs of results from SWARM and the GIS-based calculator. The red-dotted line indicates the 1:1 line. Deviation from the 1:1 line is due to the homogenous soils assumption in SWARM.

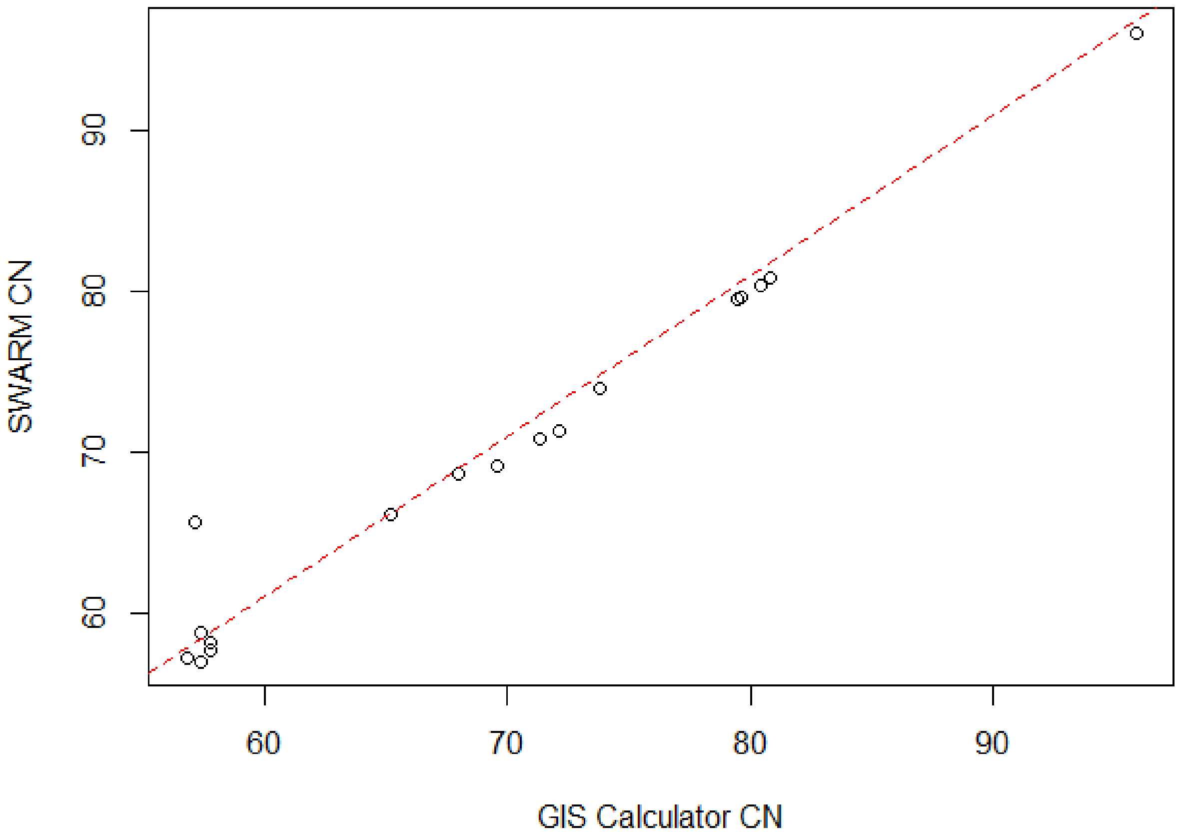


Figure 3. Effect of using impervious surface layers in the GIS Stormwater Calculator. Positive values indicate that the estimations when including the impervious layer are lower than when these layers are not considered.

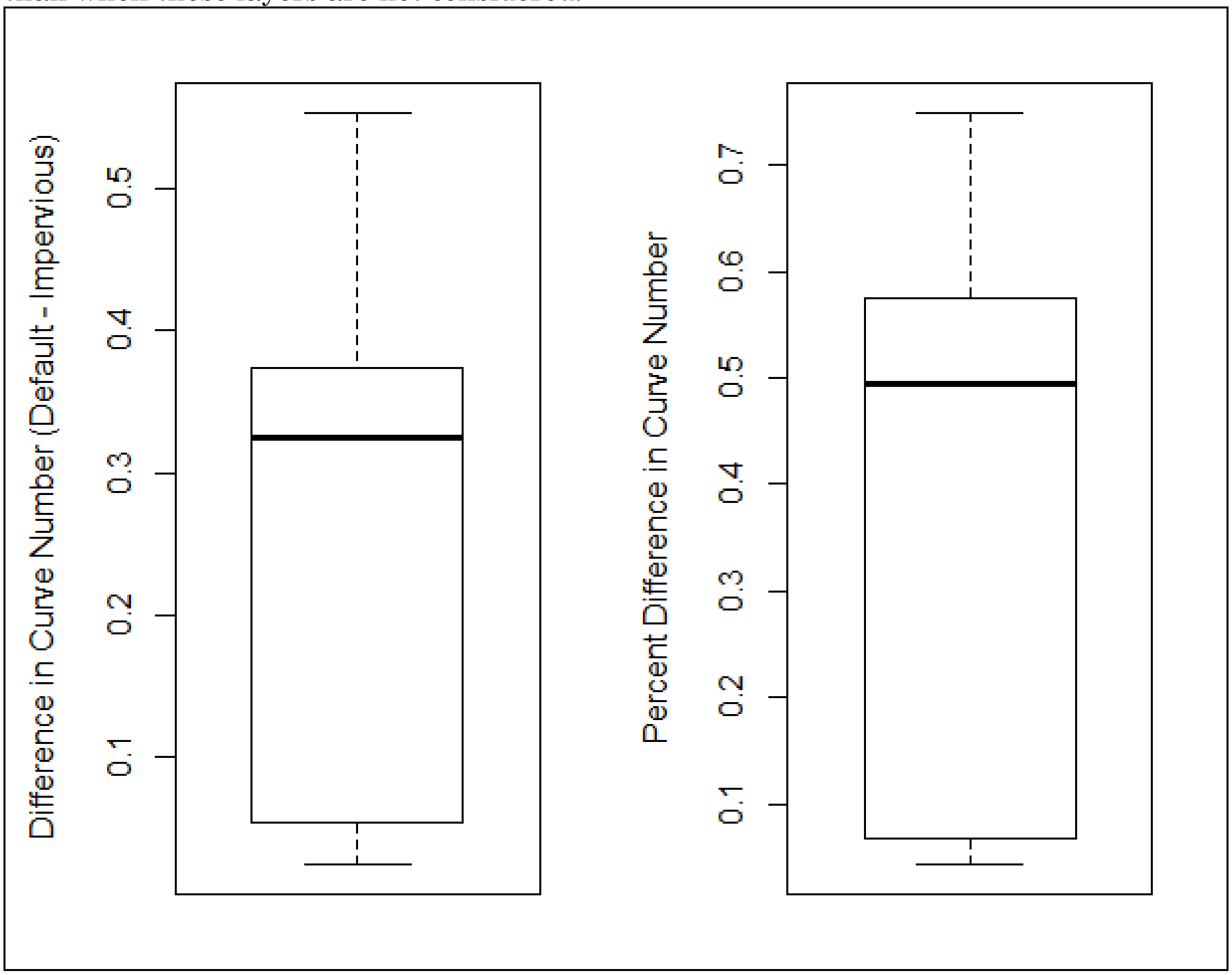


Figure 4. Withers & Ravenel and GIS Stormwater Calculator estimates of runoff. The watersheds of Bradley, Hewletts, and Howe Creeks are highly developed, while Mattamuskeet Drainage Association and Williston Creek watersheds are primarily covered by agriculture and forests. The GIS-based calculator was used with the same precipitation values as those used by Withers & Ravenel in their calculations. The lower values of the GIS-based results using the engineers' parameters show the effect of including disconnection of impervious surfaces and unmodified developed soil classes in the model. This effect is only apparent in the highly developed watersheds.

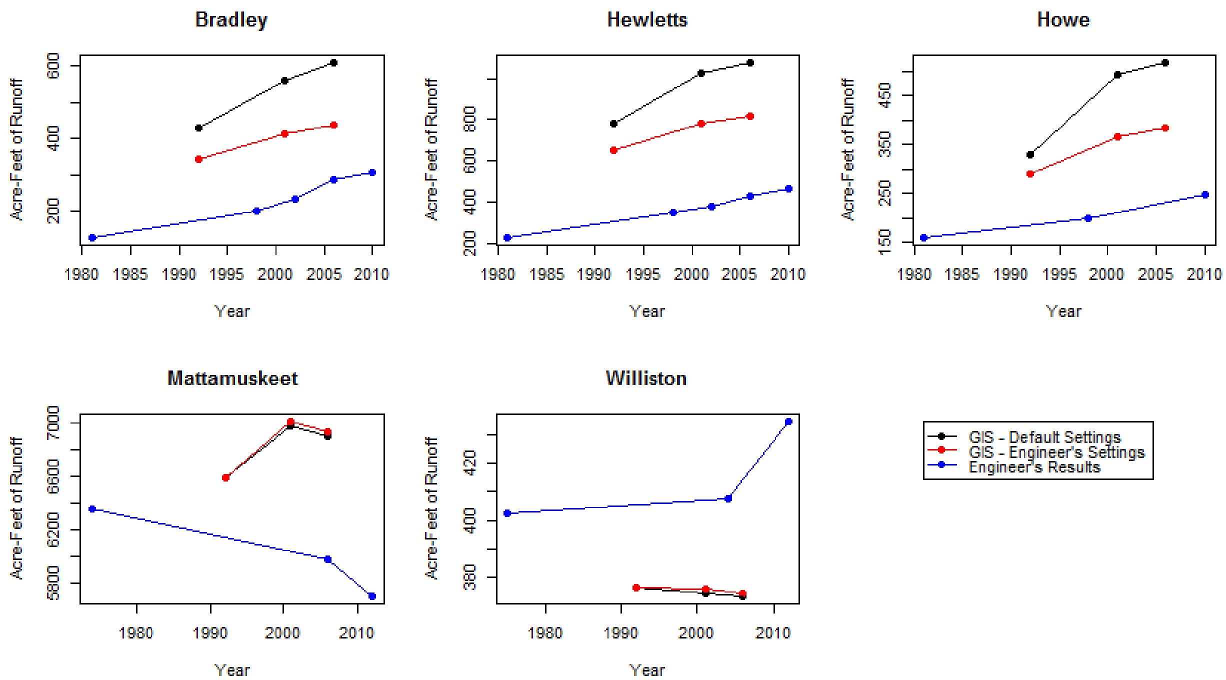


Table 1. Example GIS Stormwater Calculator Output. The tool was run with the default settings for the Deer Creek Watershed. The output table is written in a tab delimited text file and is readily examined and manipulated in Excel or other spreadsheet software.

In the text file the output will look like this:

```
Year    Composite CN20 Composite CN05 Runoff(Inches) Runoff(Cubic Ft)       Runoff (Acre ft)
1992    50.667217      35.433319      0.360007       1118634 25.68
2001    69.149909      57.382340      1.008569       3133885 71.94
2006    69.470512      57.805670      1.024076       3182069 73.05
```

In an Excel worksheet the table will look like this:

Year	Composite CN20	Composite CN05	Runoff(Inches)	Runoff(Cubic Ft)	Runoff (Acre ft)
1992	50.667217	35.433319	0.360007	1118634	25.68
2001	69.149909	57.38234	1.008569	3133885	71.94
2006	69.470512	57.80567	1.024076	3182069	73.05

Table 2. 1992 Impervious Surface Proxy Layer Curve Numbers.

Assigned CN					
Land Use Code	Land Use Class	A	B	C	D
21	Low Intensity Residential	57	72	81	86
22	High Intensity Residential	77	85	90	92
23	Commercial / Industrial / Transportation	85	90	92.5	94
Proxy Impervious CN					
Land Use Code	Equivalent Impervious Surface Proportion	A	B	C	D
21	31%	57.29	72.47	81.44	85.58
22	65%	77.35	85.05	89.6	91.7
23	78%	85.02	89.86	92.72	94.04

Table 3. Drained and Undrained Forest Area Curve Numbers

	A Soils	B Soils	C Soils	D Soils
Undrained	30	55	70	77
Drained	45	66	77	83

Table 4. Example SWARM Input Table.

Precipitation is 3.65830277476 inches

The soils of the watershed are summarized below.

Soil Code	Area (sqft)
1	31552124.3956
2	2683432.13312
4	3051556.39687

The landcover of the watershed is summarized below.

2001 landcover

LC Code	Area (sqft)
11	2315307.86937
21	13639972.72
22	6112800.27437
23	1017185.46562
24	271249.4575
42	5667176.16562
43	891248.2175
52	3807179.88562
71	1230310.03937
81	213124.57375
82	3138743.7225
90	135624.72875
95	1714684.07062

2006 landcover

LC Code	Area (sqft)
11	2315307.86937
21	13872472.255
22	6209675.08062
23	1017185.46562
24	513436.473125
42	5269989.46
43	891248.2175
52	3497180.50562
71	1772808.95437
81	213124.57375
82	2731869.53625
90	135624.72875
95	1714684.07062

Appendix A: GIS Stormwater Calculator Instructions
Scope & Requirements

The Stormwater Calculator package is designed for use with small coastal watersheds in North Carolina. Map 1 shows the area that is covered by the embedded data – all entered watersheds must fall within this area.

ArcGIS 10.2 or higher is required to run the Stormwater Calculator.

Operation

Getting Started

- Download and uncompress the Stormwater Calculator package. Be sure to place the workspace on a local drive. Running the tool remotely greatly increases the chances that it will fail.
- Open the workspace and open the accompanying map document
- Put your watershed boundary file in the 'Data' folder within the workspace. This file can be either a polygon feature class or shapefile
- Open the ArcToolbox window, the only toolbox available will be the stormwater calculator

Basic Operation

- Double click on the Stormwater Calculator script tool in the Stormwater Calculator toolbox (either in the ArcToolbox window or from the Catalog)
- An example prompt is shown in Figure 1
- Enter the path to your watershed boundary file in the first line
- If you wish to use a different precipitation value than that of the 1-yr, 24-hr storm, uncheck the 'Use NOAA 1-yr, 24-hr Precipitation Data' option and enter the desired precipitation depth (in inches) in the 'Precipitation (inches)' line
- Enter the path where you would like the output table to be written in the space labeled 'Output Table.' Be sure to include the '.txt' extension on the filename
- Enter optional parameters (see below) or click 'Ok' to run the tool.

Options

1. Impervious Surfaces – when checked the tool will sample impervious surface percentage rasters in place of the land cover rasters for all pixels in a developed land class. This allows for higher resolution calculations of composite curve numbers, particularly in urban watersheds. Higher resolution only exists for the 2001 & 2006 land cover datasets.
2. Assume all developed soils are HSG D? – this default calibration measure assumes that all soils under pixels in any of the developed classes take on the hydrologic soil group D. The logic behind this is that during development, earth moving and compaction from heavy machinery changes the hydrologic function of the soils, reducing their capacity for infiltration.
3. Impervious Surface Considerations
    a. Percent Impervious Area Disconnected (1992, 2001, & 2006) – enter the percentage (0 – 100) of impervious area that is thought to be disconnected for each of these years. This allows the user to not only try to dial in estimates using custom information about the watershed, but also allows them to test out the effects of disconnection in their watershed. This experimental use allows the user to see how disconnection scenarios will help achieve their reduction goals.
    b. Disconnected Impervious Surfaces Proportion Cutoff – this value indicates the level of impervious surface of a pixel where disconnection no longer improves the infiltration capacity of that pixel. The default value is that suggested in the NRCS Technical Report 55 – Urban Hydrology for Small Watersheds. The use of this value is recommended unless there is a specific case where the user may find some other value useful or more appropriate (e.g. in comparing the results of the Stormwater Calculator with other methods of estimation).
4. Forestry Drainage Consideration
    a. Consider drained areas for silviculture? – when this option is checked the tool will use the polygons provided in the next three parameters to change the runoff characteristics of any pixels in a forest class that are contained within the shapes. The effect is to increase runoff from these areas, simulating the change in hydrology due to draining. If this option is checked, polygon

shapefiles or feature classes must be entered for each year in the follow three parameters.

   b. Drained Forest Areas 1992, 2001, & 2006 – enter polygon shapefiles or feature classes here that encompass areas drained for forestry for each year. You must check the 'Consider drained areas for silviculture?' box and provide data for each year in order to use this option.

5. SWARM Input Table (see 'Custom SWARM Worksheet' for more information)
   a. Export SWARM Input Table – with this option checked, the tool will export a simple text file that contains all the necessary information (land use & soils summaries and precipitation) to use as the input to the custom SWARM calculator included in the tool package.
   b. SWARM Table Location – provide the path where you would like the tool to write the SWARM input table. Be sure to check the box in the parameter above in order to actually export the table.

Results

The GIS Stormwater Calculator writes a tab delimited text file to the location specified. This file contains calculated curve numbers and runoff estimates for each year of data (1992, 2001, & 2006). This file can easily be opened in Excel or another spreadsheet program for easy interpretation.

Stormwater volume targets that can be used for watershed restoration planning can be obtained by subtracting the older runoff volumes from the most recent estimate. The CN05 column shows the calibrated composite curve number for each year (where the estimate of $I_a = 0.05S$ in the runoff calculation). If you would like to compare curve numbers with a method that does not use this calibration, these curve numbers are provided in the column labeled CN20.

Custom SWARM Workbook

Included in the tool package is an Excel workbook titled 'Custom_SWARM_calculator.xlsx.' This tool is based on a template tool designed and distributed by the NOAA's National

Ocean Service, National Centers for Coastal Ocean Science. The methods in this tool are described by Blair et al. (2014). The GIS Stormwater Calculator uses the same calculations and calibrations as are used in the SWARM calculator. The primary difference in calculation is that the SWARM tool assumes that proportion of soil types underlying each land cover types is equal to the proportion of soil types in the entire watershed. You can use the custom SWARM workbook if you are interested in how this assumption changes the results for a given watershed or you would like to see some of the architecture of the calculation.

To use the workbook, you will need to check the 'Export SWARM Input Table' option in the GIS Stormwater Calculator tool and provide a path for the resulting table when you run the tool for your watershed. The resulting table contains a summary of land use and soils information and the precipitation value used in the calculation for the 2001 and 2006 tabulations (see Table 1 for an example SWARM output).

Table 1. Example SWARM Table output

```
Precipitation is 3.65830277476 inches

The soils of the watershed are summarized below.
Soil Code  Area (sqft)
1    31552124.3956
2    2683432.13312
4    3051556.39687


The landcover of the watershed is summarized below.
2001 landcover
LC Code    Area (sqft)
11   2315307.86937
21   13639972.72
22   6112800.27437
23   1017185.46562
24   271249.4575
42   5667176.16562
43   891248.2175
52   3807179.88562
71   1230310.03937
81   213124.57375
82   3138743.7225
90   135624.72875
95   1714684.07062

2006 landcover
LC Code    Area (sqft)
11   2315307.86937
21   13872472.255
22   6209675.08062
23   1017185.46562
24   513436.473125
42   5269989.46
43   891248.2175
52   3497180.50562
71   1772808.95437
81   213124.57375
82   2731869.53625
90   135624.72875
95   1714684.07062
```

Once you have exported the SWARM input table from the GIS tool, open the SWARM excel workbook. The first tab, 'Notes,' provides some simple information about the tool and the rest of the workbook. Navigate to the third tab, 'GIS_Output_to_SWARM_Conversion.' You will input the data from the exported SWARM table into these. You can simply copy and paste the information from the text file into these cells. Be careful about copying this information from other Excel worksheets, this seems to clear out the links to those cells and interrupts the calculator. The best method is to copy and paste the information directly from the text file.

The output information is contained in the sixth sheet, '3-Volume_Calculation.' This sheet contains the calculation details and the output runoff volumes.

Appendix B: Curve Number Reference

Table A. GIS Stormwater Calculator Curve Numbers. This is a table based off of the raw curve number reference file used by the stormwater calculator. Land cover codes 25, 26, 27, 32, 33, 51, 61, 83, 84, 85, 91, & 92 are specific to the 1992 data. The developed classes (25, 26, & 27) were reclassified from their original values to allow their specific consideration in the model. Land cover codes 21, 22, 23, 24, 52, 90, & 95 are specific to the 2001 & 2006 data. Land cover codes 44, 45, & 46, those that refer to drained forest classes are used when the option to consider drained areas for silviculture is checked.

Land Cover		Hydrologic Soils Group			
Code	Class	A	B	C	D
11	Water	100	100	100	100
21	Developed, Open Space	45	65	77	82
22	Developed, Low Intensity	58	73	82	86
23	Developed, Medium Intensity	77	85	90	92
24	Developed, High Intensity	89	92	94	95
25	Low Intensity Residential	57.29	72.47	81.44	85.58
26	High Intensity Residential	77.35	85.05	89.6	91.7
27	Commercial / Industrial / Transportation	85.02	89.86	92.72	94.04
31	Barren Land	76	85	89	91
32	Quarries / Strip Mines / Gravel Pits	76	85	89	91
33	Transitional	77	86	91	94
41	Deciduous Forest	30	55	70	77
42	Evergreen Forest	30	55	70	77
43	Mixed Forest	30	55	70	77
44	Deciduous Forest, Drained	45	66	77	83
45	Evergreen Forest, Drained	45	66	77	83
46	Mixed Forest, Drained	45	66	77	83
51	Shrubland	30	48	65	73
52	Shrub / Scrub	30	48	65	73
61	Orchards / Vineyards / Other	32	58	72	79
71	Grasslands / Herbaceous	39	61	74	80
81	Pasture / Hay	39	61	74	80
82	Row Crops / Cultivated Crops	72	81	88	91
83	Small Grains	65	76	84	88
84	Fallow	77	86	91	94
85	Urban / Recreational Grasses	49	69	79	84
90	Woody Wetlands	30	55	70	77
91	Woody Wetlands	30	55	70	77
92	Emergent Herbaceous Wetlands	98	98	98	98
95	Emergent Herbaceous Wetlands	98	98	98	98

Appendix C: Stormwater Calculator Results

Table A. GIS Stormwater Calculator Runoff Estimates. This table shows the results of the GIS based calculator using both the default settings and using the assumption that 50% of impervious surfaces are disconnected.

Bradley Creek

Year	CN	Acre-feet	Cubic-feet	Inches
No Disconnection Assumptions				
1992	57.18	415.22	18,087,111	1.117
2001	65.23	542.29	23,621,946	1.459
2006	67.96	590.21	25,709,730	1.588
Impervious Areas are 50% Disconnected				
1992	57.18	415.22	18,087,111	1.117
2001	64.55	530.80	23,121,452	1.428
2006	67.22	576.88	25,128,987	1.552

Hewletts Creek

Year	CN	Acre-feet	Cubic-feet	Inches
No Disconnection Assumptions				
1992	60.83	760.50	33,127,461	1.277
2001	69.57	1001.13	43,609,114	1.681
2006	71.32	1054.61	45,938,883	1.771
Impervious Areas are 50% Disconnected				
1992	60.83	760.50	33,127,461	1.277
2001	68.81	978.61	42,628,115	1.643
2006	70.51	1029.66	44,851,903	1.729

Howe Creek

Year	CN	Acre-feet	Cubic-feet	Inches
No Disconnection Assumptions				
1992	59.42	336.80	14,670,977	1.205
2001	72.17	502.76	21,900,026	1.798
2006	73.82	527.51	22,978,533	1.887
Impervious Areas are 50% Disconnected				
1992	59.42	336.80	14,670,977	1.205
2001	71.24	489.11	21,305,503	1.750
2006	72.83	512.55	22,326,689	1.833

Mattamuskeet

Year	CN	Acre-feet	Cubic-feet	Inches
No Disconnection Assumptions				
1992	78.82	5948.84	259,131,406	1.805
2001	80.81	6318.30	275,224,981	1.918
2006	80.39	6240.23	271,824,208	1.894
Impervious Areas are 50% Disconnected				
1992	78.82	5948.84	259,131,406	1.805
2001	80.72	6302.73	274,547,087	1.913
2006	80.31	6224.84	271,153,876	1.889

Williston Creek

Year	CN	Acre-feet	Cubic-feet	Inches
No Disconnection Assumptions				
1992	79.78	384.50	16,748,993	2.101
2001	79.61	382.62	16,666,802	2.090
2006	79.47	381.12	16,601,688	2.082
Impervious Areas are 50% Disconnected				
1992	79.78	384.50	16,748,993	2.101
2001	79.54	381.89	16,635,263	2.087
2006	79.40	380.40	16,570,256	2.078

Deer Creek

Year	CN	Acre-feet	Cubic-feet	Inches
No Disconnection Assumptions				
1992	35.43	25.68	1,118,634	0.360
2001	57.38	71.94	3,133,885	1.009
2006	57.81	73.05	3,182,069	1.024
Impervious Areas are 50% Disconnected				
1992	35.43	25.68	1,118,634	0.360
2001	56.72	70.23	3,059,032	0.984
2006	57.14	71.31	3,106,356	1.000

Table A. (continued)

Boathouse Creek

No Disconnection Assumptions

Year	CN	Acre-feet	Cubic-feet	Inches
1992	41.66	26.50	1,154,286	0.517
2001	56.81	50.72	2,209,400	0.989
2006	57.79	52.56	2,289,377	1.025

Impervious Areas are 50% Disconnected

Year	CN	Acre-feet	Cubic-feet	Inches
1992	41.66	26.50	1,154,286	0.517
2001	56.23	49.64	2,162,365	0.968
2006	57.20	51.45	2,241,043	1.003

Dubling Creek

No Disconnection Assumptions

Year	CN	Acre-feet	Cubic-feet	Inches
1992	55.97	18.48	805,027	0.959
2001	57.16	19.31	841,108	1.002
2006	57.16	19.31	841,108	1.002

Impervious Areas are 50% Disconnected

Year	CN	Acre-feet	Cubic-feet	Inches
1992	55.97	18.48	805,027	0.959
2001	57.13	19.28	839,920	1.000
2006	57.13	19.28	839,920	1.000

Hills Bay

No Disconnection Assumptions

Year	CN	Acre-feet	Cubic-feet	Inches
1992	43.15	8.21	357,750	0.558
2001	57.40	14.89	648,646	1.012
2006	57.40	14.89	648,646	1.012

Impervious Areas are 50% Disconnected

Year	CN	Acre-feet	Cubic-feet	Inches
1992	43.15	8.21	357,750	0.558
2001	56.91	14.63	637,110	0.994
2006	56.91	14.63	637,110	0.994

Highway 24 Area

No Disconnection Assumptions

Year	CN	Acre-feet	Cubic-feet	Inches
1992	91.95	14.65	638,216	2.917
2001	95.86	16.37	712,888	3.259
2006	95.86	16.37	712,888	3.259

Impervious Areas are 50% Disconnected

Year	CN	Acre-feet	Cubic-feet	Inches
1992	91.95	14.65	638,216	2.917
2001	95.44	16.17	704,291	3.219
2006	95.44	16.17	704,291	3.219

Table B. Withers & Ravenel Stormwater Runoff Estimates. This table shows the estimates generated by the engineering firm Withers & Ravenel as contracted by the North Carolina Coastal Federation.

Bradley Creek			
Year	Acre-feet	Cubic feet	
1981	126.81	5,523,931	
1998	200.89	8,750,812	
2002	234.33	10,207,415	
2006	288.54	12,568,672	
2010	307.67	13,402,236	
Hewletts Creek			
Year	Acre-feet	Cubic feet	
1981	225.44	9,820,210	
1998	348.68	15,188,588	
2002	375.96	16,376,818	
2006	433.10	18,865,705	
2010	462.95	20,165,971	
Howe Creek			
Year	Acre-feet	Cubic feet	Inches
1981	159.28	6,938,440	0.570
1998	198.70	8,655,389	0.711
2010	249.43	10,865,167	0.892
Mattamuskeet			
Year	Acre-feet	Cubic feet	Inches
1974	6358.71	276,985,229	1.930
2006	5971.25	260,107,729	1.812
2012	5691.34	247,914,637	1.727
Williston Creek			
Year	Acre-feet	Cubic feet	Inches
1975	402.56	17,535,644	2.199
2004	407.48	17,749,892	2.226
2012	434.46	18,924,929	2.374